

## U.S. Fish and Wildlife Service

### Natural Log Jams in the White River: Lessons for Geomimetic Design of Engineered Log Jams

---



Robes Parrish and Peter Jenkins

U.S. Fish and Wildlife Service  
Mid-Columbia River Fishery Resource Office  
Leavenworth, WA 98826

***On the cover:** Deflector-type log jam in White River, eastern Cascade Mountains, WA.  
USFWS photograph by Robes Parrish.*

*The correct citation for this report is:*

Parrish, R.M. and Jenkins, P.B. 2012. Natural Log Jams in the White River: Lessons for Geomimetic Design of Engineered Log Jams. U.S. Fish and Wildlife Service, Leavenworth, WA.

**NATURAL LOG JAMS IN THE WHITE RIVER:  
LESSONS FOR GEOMIMETIC DESIGN OF ENGINEERED LOG JAMS**

*Study funded by*

U.S. Fish and Wildlife Service  
Portland, OR.

*and authored by*

Robert “Robes” M. Parrish  
Peter B. Jenkins

U.S. Fish and Wildlife Service  
Mid-Columbia River Fishery Resource Office  
7501 Icicle Road  
Leavenworth, WA 98826

Final Report  
February, 2012

### **Disclaimers**

Any findings and conclusions presented in this report are those of the authors and may not necessarily represent the views of the U.S. Fish and Wildlife Service.

The mention of trade names or commercial products in this report does not constitute endorsement or recommendation for use by the federal government.

NATURAL LOG JAMS IN THE WHITE RIVER:  
LESSONS FOR GEOMIMETIC DESIGN OF ENGINEERED LOG JAMS

Robes Parrish and Peter B. Jenkins

*U.S. Fish and Wildlife Service  
Mid-Columbia River Fishery Resource Office  
7501 Icicle Rd.  
Leavenworth WA 98826*

**Abstract-** Accumulation of woody material (WM) is an important component of Pacific Northwest stream systems. Many streams in the Upper Columbia Basin were historically cleared of WM which has contributed to diminished habitat quality for native fishes. Groups in this region are actively involved in restoring these habitats, largely for the benefit of ESA-listed salmonids. Many of these efforts include creating engineered log jams (ELJs) as a component of designs. Most ELJ designers rely heavily on generalized numerical models and utilize large rock and cable as ballast to provide an added factor of safety sufficient to maintain stability over the structure's lifespan. We hypothesized that log jams can be naturally stable and that time-series and geomorphic analysis may yield practical information for ELJ design. This study examined long-lived (>10 years), naturally stable WM accumulations in a low-gradient (<0.2%), alluvial system in order to provide design data for a current project in an analogous reach. Log jams were classified as either mid-channel or streambank-associated (i.e., deflector). Historical air photo analysis validated their temporal longevity on the landscape, which ranged from 12 – 41+ years old. At five of these sites we measured the structural elements of each log jam to determine the components which beget stability. It is unclear which individual attributes are most important for maintaining long-term stability within this geomorphic and hydrologic setting (e.g., diameter, length, orientation, volume), however, collectively, these attributes contributed to stable log jams. We consider natural WM accumulations to be persistent if key and secondary members remain intact even as racked members are added or shed. ELJ project goals should seek stability and persistence in order to create a dynamic riverine environment. Furthermore, watershed-scale processes may not be fully restored unless numerous, large ELJs are constructed throughout a reach with a reduced reliance on excessive rock, artificial ballast and cable. Based on this work, we suggest that restoration practitioners utilize geomimetic design by collecting data from reference log jams to increase confidence in numerical model predictions, create better artificial habitats, and to achieve process-based restoration goals.

*Page intentionally left blank for 2-sided printing*

## Table of Contents

<i>Abstract</i> .....	i
<b>List of Tables</b> .....	iv
<b>List of Figures</b> .....	iv
<b>Introduction</b> .....	1
<b>Study Area</b> .....	2
<b>Methods</b> .....	3
<b>Results</b> .....	6
<i>Aerial Photo Analysis</i> .....	7
<i>WM Size</i> .....	7
<i>Orientation</i> .....	9
<i>Rootwads and Depositional Islands</i> .....	10
<i>Avulsions</i> .....	10
<b>Discussion</b> .....	10
<i>Persistence</i> .....	10
<i>Log Size</i> .....	11
<i>Orientation Patterns</i> .....	12
<i>Depositional Patterns</i> .....	12
<i>Reach-Scale Accumulation Patterns and Loading</i> .....	13
<i>Geomimetic Design</i> .....	13
<i>Opportunities for Improving ELJ Designs</i> .....	14
<i>Regional Differences</i> .....	16
<i>Additional Questions/Future Research</i> .....	17
<b>Acknowledgments</b> .....	19
<b>Literature Cited</b> .....	20
<b>APPENDIX A</b> .....	23

### **List of Tables**

Table 1. Typology of woody material in log jams used for this study. ....	4
Table 2. Mid-channel (bar apex) log jam characteristics in the White River. ....	6
Table 3. Deflector-type log jam characteristics in the White River. ....	7
Table 4. Results of Kruskal-Wallis one-way analysis of variance (ANOVA) on ranks and multiple pairwise comparisons for significance (Dunn correction method).....	9

### **List of Figures**

Figure 1. Map showing log jam survey locations in White River, WA.....	3
Figure 2. Box plots showing length and DBH values for key, secondary, and raked members in mid-channel and deflector jams (combined data).....	8
Figure 3. Observed planview of deflector jams.....	9
Figure 4. Diagram showing inverse longitudinal slope of raked members.....	13
Figure 5. Aerial photo time series analysis of BA #1 and BA #2.....	22
Figure 6. Aerial photo time series analysis of DF #1 and DF #2.....	23
Figure 7. Aerial photo time series analysis of DF#3.....	24



*Page intentionally left blank for 2-sided printing*

## Introduction

Instream woody material (WM) is a common and important component of the landscape in forested, mountain environments. In the last two decades, the literature on the geomorphic and biological contributions and implications of WM in fluvial systems has expanded greatly. A meta-analysis by Lassetre and Harris (2001) notes that the literature on WM generally falls into the following categories: 1) characteristics, distribution, and transport of WM; 2) WM effects to channel morphology; 3) WM and stream ecology; and 4) land management impacts on WM recruitment. Although few studies have sought to characterize the distinct and recurrent types of WM accumulations (log jams), regional, local, and site-specific patterns and processes exist (Abbe and Montgomery, 2003). Studies within Washington seeking to characterize the distribution, extent, size, and configuration of WM in the river are generally limited to the Pacific coastal ecosystems (e.g., Robison and Beschta, 1990; Abbe and Montgomery, 2003), although one paper did examine logjam attributes in several Eastern Cascades rivers (Fox, 2003).

In the Pacific Northwest, there is a long history of river clearing for navigation, flood abatement, floodplain development, and timber production. These landscape-level changes in habitat have contributed to the general decline in salmon populations. The addition of WM to stream systems as a habitat restoration technique has gained popularity in the last 10 – 20 years. Practitioners continue to refine this tool based on the success and failure of Engineered Log Jam (ELJ) projects and the depth of technical knowledge has improved greatly over this period.

ELJs are commonly integrated into eroding streambanks as a way of reducing erosion rates while also improving habitat complexity. They are also constructed in reaches deficient in WM to create pool habitat and high-flow refugia for fish. Most ELJ projects utilize large rocks, cable, and artificial anchors, to provide the ballast sufficient to ensure stability and rigidity with a predetermined factor of safety. The available empirical models to design ELJs are derived from traditional civil engineering approaches which require designers to complete a force balance determination. These calculations parse the physical pressures acting on a logjam into its various components. Buoyancy and drag must be exceeded by the opposing forces of gravity, surcharge, passive earth pressure, channel obstructions and boundary roughness to remain stable. There are many implicit terms in these calculations which make their applicability to the riverine environment difficult, particularly when coupled with the additional uncertainties of sediment transport fluxes, substrate variability, and flood flow scour depths. Designers must also make broad assumptions about materials whose irregular and imprecise characteristics are often unknown in the design phase.

Alternatively, if natural log jams can remain stable on the landscape for many years, then many of these engineering uncertainties should be inherently captured by replicating their

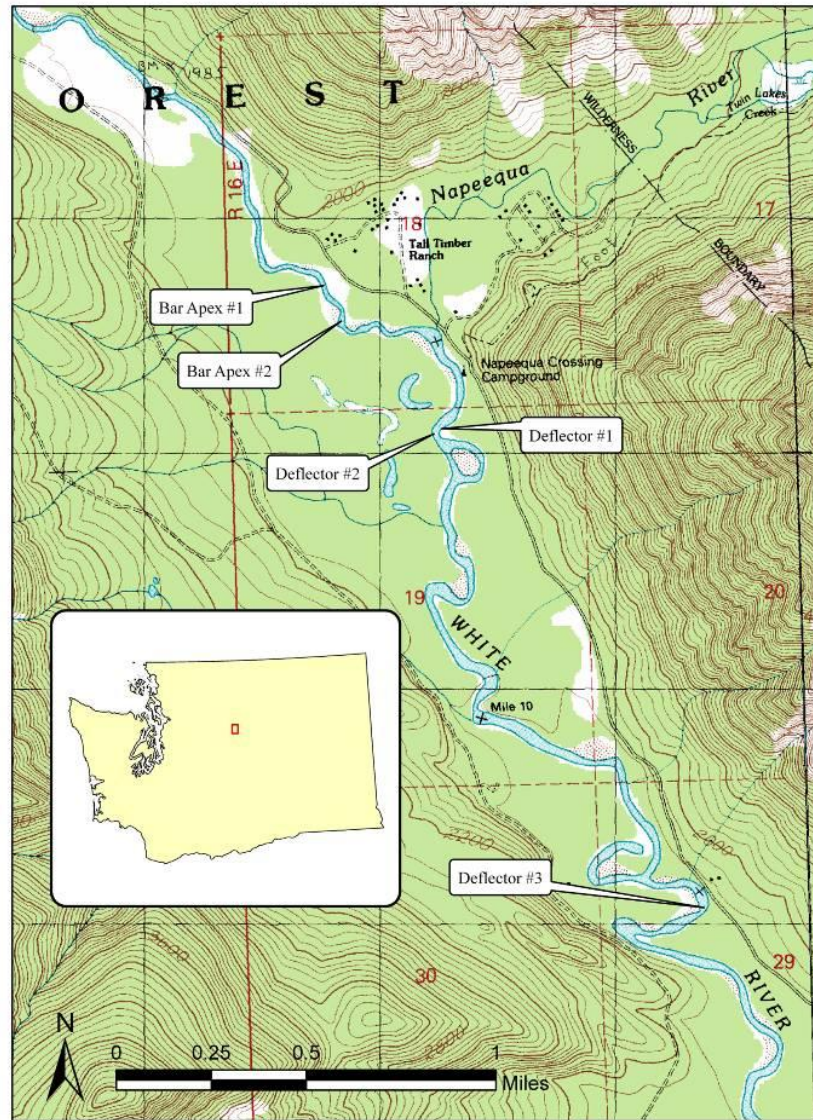
constituent elements as ELJs. This would eliminate the need for artificial ballast and provide more complex habitats. In this context, we propose using the term “geomimetics” to describe the method of studying the formative geomorphic processes, structure, and function of natural log jams to mimic in the design of engineered log jams.

Several authors have noted that natural log jams can remain in-place for considerable periods of time (Tally, 1980; Harmon et. al, 1986). They may even continue to affect floodplain and riparian forest development long after they become buried or are abandoned by the active channel (Naiman et al., 1998; Montgomery and Abbe, 2006). Stable, long-lived, natural log jams likely exist in the Upper Columbia (UC) region, though WM is below historical or desirable levels (UCSRB, 2007). UC salmon recovery groups often seek the addition of in-stream WM as a tool to directly improve salmonid habitat and facilitate the restoration of reach-scale geomorphic processes (UCSRB, 2007). In the UC, ELJ projects are often sited on tributary rivers with considerable anthropogenic development in the floodplain as a means of addressing streambank erosion or limited pool habitat. We are unaware of any mid-channel ELJ projects constructed in the UC, perhaps out of fear that they will cause avulsions or channel migration into adjacent floodplain infrastructure, or be easily lost during flood events.

The intent of our study was threefold: 1) to determine if naturally stable, persistent log jams exist in the Upper Columbia region, 2) to develop a field survey methodology sufficient to characterize the morphology of these accumulations, and 3) to determine the structural elements of natural log jams which may be replicable in the design process for restoration projects.

## **Study Area**

The White River (Chelan County, WA) was selected for study because it possesses similar attributes to the “Stillwater Reach” of the Entiat River (RM 16 – 26). The Stillwater Reach has multiple ELJ projects proposed for construction in summer, 2012. A 2007 report (Woodsmith and Bookter) analyzed a number of variables to determine the most appropriate local reference reach for restoration design considerations in the Stillwater. They identified the Chiwawa River as the best analog, with the White River a close runner-up. Ground observations of WM accumulations in the lower Chiwawa River revealed a stream type with a finer substrate composition than in the Stillwater treatment reach. In the upper Chiwawa River, key members were composed of extremely large diameter wood that was deemed infeasible to acquire for future ELJ construction. The White River, however, from RM 9 – 13 was of the same stream type, valley type, and had similar vegetative conditions to the Stillwater, with log jams comprised of moderate-sized wood. Individual survey locations are shown in Figure 1.



**Figure 1. Map showing log jam survey locations in White River, WA.**

## Methods

Our study design was predicated upon several assumptions: 1) certain watersheds are sufficiently unaltered and contain log jams that may be considered in ‘reference’ condition; 2) the formative physical processes leading to log jam development will yield similar, observable, and quantifiable results; and 3) stable, natural log jams can provide a suitable analog for replication in the design of local restoration projects.

Reference reaches must have a comparable stream type, valley type, and boundary conditions to the treatment reach of interest. Use of dimensionless ratios for geomorphic variables enables direct comparison, even for streams of different discharge and bankfull

dimensions. In this first year of data collection, only log jams in C4 stream types and U-shaped glacial trough valleys (Rosgen, 1994) with moist conifer-cottonwood riparian communities were selected because of their direct applicability to upcoming restoration opportunities in the Stillwater Reach of the Entiat River.

A field methodology to study attributes of log jams similar to Abbe and Montgomery (2003) was developed. These authors classified log jams according to their mode of recruitment and the orientation of individual pieces of WM. For our study we have distilled the ten types of WM accumulations they describe into two categories: mid-channel/bar apex and streambank-oriented/deflector. These represent the most common types of ELJ structures built in restoration practice. The definitions provided in Table 1 were used to describe individual components of the log jam to be measured.

**Table 1. Typology of woody material in log jams used for this study.**

Type of WM	Definition
<i>Key Member</i>	<i>Structural WM that, if removed, would result in a considerable portion of the log jam being lost to bankfull flows; primary stable jam components.</i>
<i>Anchor Point</i>	<i>A type of key member consisting of rooted, standing trees, stumps or boulders that contribute to the basal stability of the log jam; considered a key member but noted separately from horizontal-lying WM.</i>
<i>Secondary Member</i>	<i>The primary WM constituents, positioned against the key members or anchor points that support all of the racked material upstream; stable components.</i>
<i>Racked Member</i>	<i>WM that accumulates upstream and within the log jam; interacts with the channel over a wide range of flows and serves to dissipate considerable stream power; may not be stable or long-lived.</i>

We chose to survey only those log jams that were >10 years old because this is often considered a desirable minimum design lifespan for ELJ construction projects. Aerial photographs in several fourth-order rivers (Little Wenatchee, White, and Chiwawa Rivers) were scanned and imported into Adobe Photoshop to identify the presence of large WM accumulations considered to be in reference condition (Woodsmith and Bookter, 2007). Where they could be positively identified in the photos, mid-channel and streambank-oriented accumulations were aged by assigning a range of formation dates between available photos. The actual formation date of each jam is imprecise because of the large gaps between aerial photos (1949, 1962, 1970, 1985, 1992, 1998, 2006, 2009).

Photos were not orthorectified but jams were georeferenced (aligned) using visible features common to each picture. Field verification was then completed to determine if the jams were still present and of sufficient size to warrant survey and measurement. No specific size criteria were used to define a “log jam” but, in general, accumulations were only considered if they were comprised of multiple logs which had extensively racked material. Limitations of this method included the difficulty of identifying smaller WM accumulations, particularly those on the bank due to shadows cast by riparian trees, poor photo quality and missing photos in the Okanogan-Wenatchee National Forest records.

A total of five logjams were surveyed (2 mid-channel, 3 deflector-type) between September and October, 2010 (Figure 1). Mid-channel jams were adjacent to one another and had a contributing drainage area of 91.79 mi<sup>2</sup>, annual precipitation of 114 in., and a bankfull slope of 0.003 ft/ft. Deflector jams were downstream and had a mean contributing drainage area of 137 mi<sup>2</sup>, mean annual precipitation of 109 in., and a mean bankfull slope of 0.0005 ft/ft. A Topcon TDS-223 total station was used to collect topographic data (DEM) and to obtain channel cross-sections, a longitudinal profile, logjam dimensions, adjacent channel bathymetry, and position within the active channel. Bankfull width was measured at the cross-section which bisected the jam through the key member/anchor point (we acknowledge that a more accurate method would take width measurements at locations unaffected by the WM). Floodprone width was measured from aerial photos across the valley bottom and verified using elevation breaks from LiDAR data. All WM >6 ft. in length and 6 in. in diameter were measured with a reel tape and a logger’s tape. Many logs could not be counted because they existed below the water or ground surface. Measurements of key and secondary members included their length, diameter (DBH), compass orientation (relative to bankfull flow), rootwad dimensions, rootwad top and basal elevation, bole mid-point elevation, and embeddedness. Key members were termed ‘anchor points’ when they consisted of one or more rooted trees, vertically-oriented stumps, or large boulders that initiated subsequent WM accumulation. For anchor points, DBH, base and top elevations were recorded, although length was considered unimportant. Length was, however, recorded for key members lying horizontally (flat) on the streambed. Log orientation was measured with respect to estimated bankfull flow direction and was based on the methods of Bilby and Ward (1989) (as described in Schuett et al., 1999). For example, a rootwad (or using the larger diameter end when no rootwad was present) facing directly upstream is considered oriented 180°, while a log oriented perpendicular to flow is 90° or 270°).

Only length, diameter, orientation, and the presence of a rootwad were recorded for racked members. For logs without rootwads, diameter was measured at the thickest end (which may not always correspond exactly to diameter at breast height). Additional variables measured included: jam position within the active channel, spatial characteristics of the jam (jam length) and its associated depositional features (island

length), total number of visible logs, the presence/absence of avulsions, and sketch maps. Island length was measured from the anchor point to the end of the low-flow depositional area while jam length was measured from the anchor point to the upstream extent of racked WM.

Survey data correction and post-processing was done using TDS Foresight software, geomorphic analysis of cross-sections and longitudinal profiles were completed in RiverMorph 4.3. Statistics on log sizes were computed using SigmaPlot 12 where a Kruskal-Wallis one-way ANOVA on ranks was performed. Pairwise multiple comparisons were computed using a Bonferroni-Dunn correction test. Aerial photo analysis also utilized ArcGIS 9 to display log jams spatially within the broader reach and AutoCAD Civil 3D rendered three dimensional topographic surfaces to model each jam.

## Results

Our air photo analysis verified that certain log jams in the White River can remain stable and persist for greater than 10 years. Tables 2 and 3 provide a summary of the characteristics of key, secondary, and racked members found within each jam type.

**Table 2. Mid-channel (bar apex) log jam characteristics in the White River.**

Parameter	Minimum	Maximum	Mean	<i>n</i>
<i>General Characteristics</i>				
Persistence (yr)	12	>25	n/a	2
Bankfull width (ft)	183.9	251	217.5	2
Floodprone width (ft)	1882	2460	2171	2
Ratio island length/jam length	1.8	4.4	3.1	2
Est. total # logs	14	80	47	2
<i>Key Members</i>				
DBH (ft)	2.0	3.7	2.6	7
Length (ft)	22.7	60	43.8	6
Length as % bankfull width	12.3	24.5	20.9	6
Orientation (deg)	180	260	203	6
<i>Secondary Members</i>				
DBH (ft)	1.8	3.3	2.5	5
Length (ft)	35	89.5	60.5	5
Length as % bankfull width	16.3	48.7	31.7	5
Orientation (deg)	150	195	171	5
% with rootwads			100	5
Rootwad area (ft <sup>2</sup> )	7.8	42.4	26.3	5
<i>Racked Members</i>				
DBH (ft)	0.8	2.1	1.5	16
Length (ft)	15	59	34	16
Length as % bankfull width	6.0	32.1	17.7	16
Orientation (deg)	90	90	90	4
% with rootwads			31.6	16

**Table 3. Deflector-type log jam characteristics in the White River.**

Parameter	Minimum	Maximum	Mean	<i>n</i>
<i>General Characteristics</i>				
Persistence (yr)	12	>41	n/a	3
Bankfull width (ft)	168.9	226	197.5	3
Floodprone width (ft)	1272	2885	2079	3
Ratio island length/jam length	1.3	2.2	1.7	3
Est. total # logs	120	300	210	2
<i>Key Members</i>				
DBH (ft)	1.4	2.8	2.1	2
Length (ft)	68	115	95.3	4
Length as % bankfull width	30.1	50.9	42.2	4
Orientation (deg)	190	190	190	4
<i>Secondary Members</i>				
DBH (ft)	1.7	2.7	2.2	6
Length (ft)	15	90	55.7	6
Length as % bankfull width	7.8	39.8	26.1	6
Orientation (deg)	25	270	182.5	6
% with rootwads			83	6
Rootwad area (ft <sup>2</sup> )	19.6	55.7	32.7	5
<i>Racked Members</i>				
DBH (ft)	0.4	4.5	1.5	70
Length (ft)	8	89	33	70
Length as % bankfull width	4.7	46	17.2	70
Orientation (deg)	0	280	153.6	70
% with rootwads			34.3	70

### ***Aerial Photo Analysis***

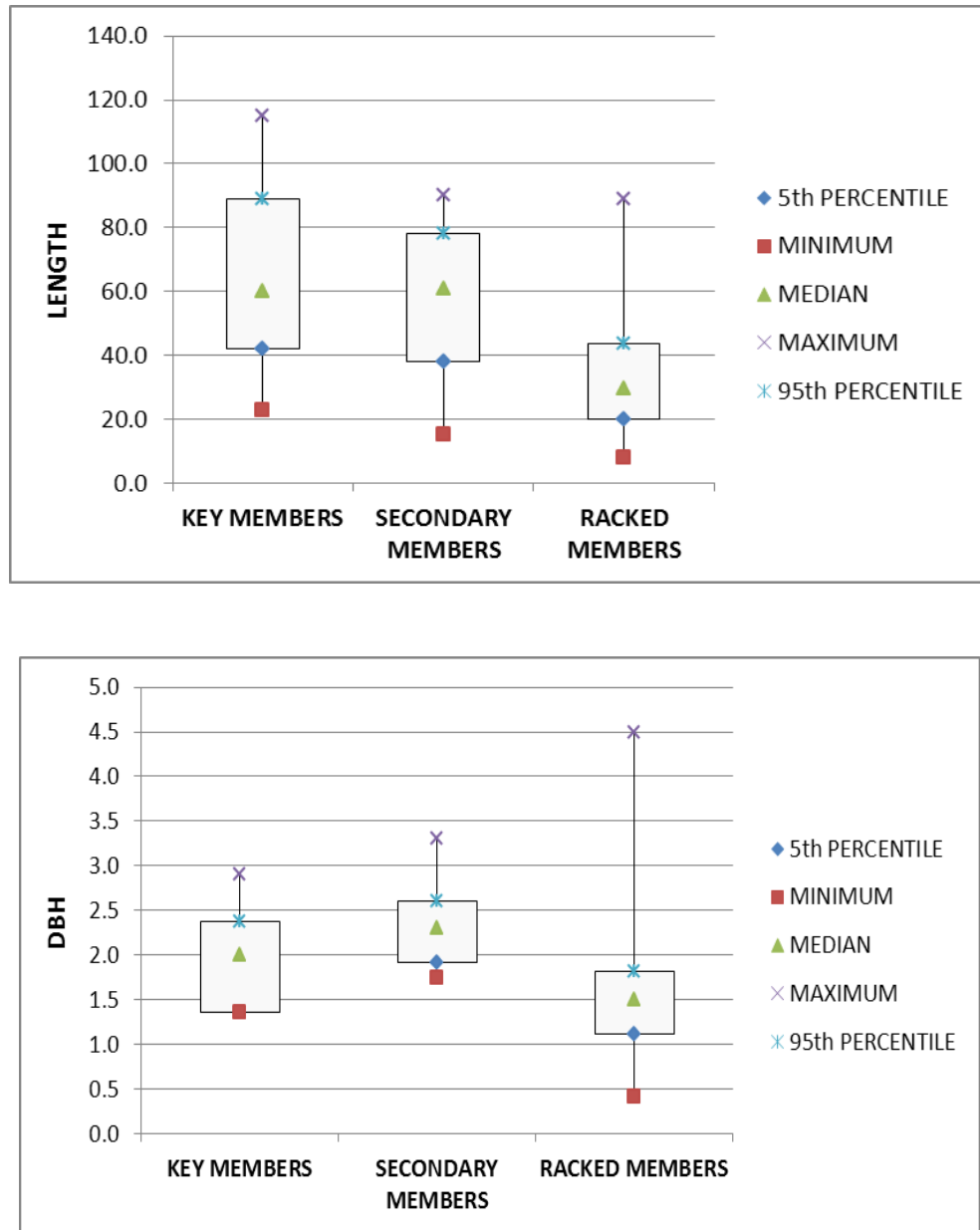
Temporal longevity of the five WM jams varied from a minimum of 12 years to >41 years, as validated using the available aerial photos. The spatial extent of each log jam can be seen to change over time but the key and secondary members remain intact. Scanned aerial photos are presented in a time sequence format in Appendix A. The presence of each jam on the landscape was only confirmed when photo evidence was definitive. In the 1949 photo, Deflector #2 may already be accumulating WM against what later became the anchor points, however, this was inconclusive.

### ***WM Size***

Log length and DBH data were subjected to statistical analysis to determine if there is a size difference between key, secondary, and racked pieces. The combined results for deflector and mid-channel jams are shown in Figure 2, while the Kruskal-Wallis ANOVA and post-hoc pairwise comparisons are shown in Table 4. For both length and DBH, there is no statistical difference ( $p < 0.05$ ) between key and secondary members. However, racked pieces are significantly smaller in diameter and are shorter, indicating that larger pieces are indeed more likely to become formative elements in a jam. Larger logs may become entrained as racked pieces once a jam is established (e.g., maximum



length values shown in Figure 2), but only large and/or long trees become key and secondary pieces. The statistical exception to this finding is that DBH was not significantly different between key and racked members ( $p > 0.05$ ), although the sample size was small ( $n = 10, 86$ , respectively).



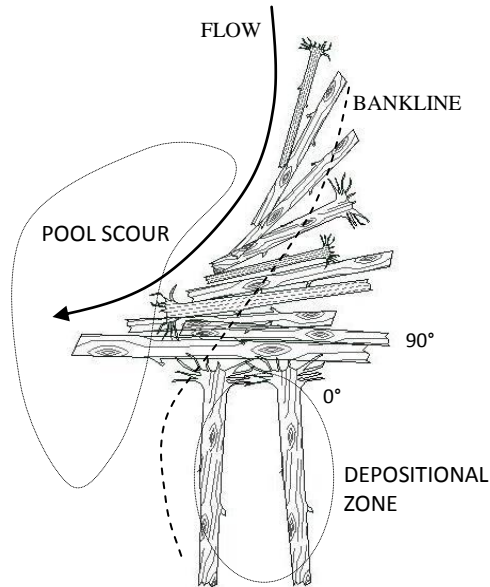
**Figure 2. Box plots showing length and DBH values for key, secondary, and racked members in mid-channel and deflector jams (combined data).**

**Table 4. Results of Kruskal-Wallis one-way analysis of variance (ANOVA) on ranks and multiple pairwise comparisons for significance (Dunn correction method).**

Comparative Elements (median values)	H	df	Q	P-value
<i>Length (ft)</i>	17.777	2		<0.001
Key (60), Secondary (61)			0.398	>0.05
Key (60), Racked (29.5)			3.33	<0.05
Secondary (61), Racked (29.5)			2.931	<0.05
<i>DBH (ft)</i>	18.110	2		<0.001
Key (2.0), Secondary (2.3)			1.388	>0.05
Key (2.0), Racked (1.5)			1.978	>0.05
Secondary (2.3), Racked (1.5)			3.957	<0.05

### ***Orientation***

The orientation of individual pieces within the jam followed a predictable pattern. Key and secondary members for both jam types were generally aligned parallel to the high flow direction with root wads facing upstream. Racked members within mid-channel jams were aligned perpendicular to flow and appear to reduce much of the incoming stream energy in front of the key pieces. Deflector jams had more variability, with the upstream pieces often deposited at 0°/180° along the bank, while those pieces closest to the key members were aligned 90°/270° (Figure 3).



**Figure 3. Observed planview of deflector jams. Note rotational pattern of racked members gradually redirects flow and promotes additional deposition over boles of key members.**

### ***Rootwads and Depositional Islands***

All key members had root wads, whether lying horizontally on the streambed or vertically as part of rooted trees and stumps (anchor points). Within bar-apex jams, 100% of secondary members and 31.6% of racked members had rootwads, while 83% of secondary members and 34.3% of racked members still had attached roots in deflector jams. The length of the depositional bar formed in the lee of key members averaged  $3.1 * L_{WM}$  (where  $L_{WM}$  = longitudinal WM jam length) for bar apex jams and  $1.7 * L_{WM}$  for deflector jams.

### ***Avulsions***

The WM jams studied did not appear to have initiated meander chute cutoffs (avulsions), as has been documented by other observers (e.g., Brummer et al., 2006). However, each structure surveyed did have a flanking high-flow channel but was not significant enough to shorten low-flow channel length and/or change the local bankfull slope. In other reaches of the White River we observed instances where extensive WM accumulations seem to maintain very tight radius meanders, perhaps preventing avulsions. However, data was not collected to determine these relationships, particularly given the complexities associated with varying local boundary conditions.

## **Discussion**

Our study was an initial attempt at trying to understand what physical elements make log jams in the Upper Columbia region stable and persistent. We present our findings about the longevity, size, orientation, and accumulation patterns of WM accumulations in this area and suggest that using reference log jams as a template for ELJ design (geomimetics) is an under-utilized tool within the restoration community. Additionally, we present several observations which, when incorporated into designs, would better emulate natural log jams.

### ***Persistence***

While our air photo analysis was imprecise for determining the exact age of each WM jam studied, it demonstrates that natural log jams can persist on the landscape for many decades in the White River. Most authors and restoration professionals describe the success of constructed jams in terms of their ability to remain “stable” over-time. If the objective of an ELJ project is to construct structures which merely remain intact, then it is logical to measure success based on how well all logs are retained. If individual logs in an ELJ are lost to high-flows or the structure is significantly deformed, then it is typically considered a failure. However, the extent of racked members in natural log jams may

shrink or grow in size over time while the key and secondary members still remain intact. Therefore, if achievement of “naturally functioning” is an objective, we suggest that it is more appropriate to describe ELJ project objectives in terms of *persistence* instead of stability. If the structure diminishes in size over time, it may not necessarily be a failure because it can still contribute a great deal to the dynamic fluvial environment. The cyclical recruitment of new WM and loss of some racked members creates a productive micro-habitat for fishes and provides heterogeneity within the fluvial landscape. Many Upper Columbia ELJ projects create a static habitat because they are rigidly designed to retain all logs and even shed incoming WM. Cabled logs that are dislodged from ELJ structures also pose a significant safety hazard and are often removed from the river downstream. We believe the use of rigid, stable ELJ structures is best suited for bank revetment projects.

### ***Log Size***

Others have reported that log size (length and/or DBH) is an important variable which promotes stability and thus WM jam formation (e.g., Bilby and Ward, 1989; Braudrick and Grant, 2000; Abbe and Montgomery, 2003). In western Cascade rivers of the Pacific Northwest, Bilby and Ward (1989) found that trees longer than one-half the bankfull width are generally stable within small streams, particularly if they have a diameter greater than the bankfull depth. Within the Queets watershed where bankfull widths are considerably wider than the maximum length of available WM, Abbe and Montgomery (2003, Figure 12) used the ratio of diameter to bankfull depth plotted against length to bankfull width to distinguish log stability thresholds. We did not measure bankfull depth in riffles and therefore cannot analyze length and DBH as integrative of overall log size. Available data on WM size and channel cross-sections from the White River suggest that trees smaller than in the Queets River can still form key members.

Our ANOVA comparison among WM types shows no significant size difference between key and secondary members, though both are almost always significantly larger than racked members (Table 4). Since it appears that key members in the White River may be as small as 1.4 ft. DBH and sometimes as short as 23 ft., we hypothesize that size alone is not the only variable which begets stability. The amount of racked material protecting the key members from scour, WM orientation, jam position within the channel, and adjacent pool volume (to dissipate energy) are all factors which may be as important to stability as WM size.

Mean key member size is >2 ft DBH and 70+ ft long when averaged for both jam types. Hicks et al. (1991) suggest that unless large-scale events such as extensive blowdown occurs, WM in impaired channels will be of insufficient size or quantity to form key members for 50-100 years in western Cascades and coastal Alaskan ecosystems. Growth rates for common coniferous riparian species in the eastern Cascades such as Ponderosa

Pine and Douglas Fir are considerably slower and may not reach key member size until 75-200 years of age. Cottonwood trees grow faster, however, their soft wood is easily broken in the fluvial environment and their contribution as key and secondary members in log jams seems to be less than conifer species. Tree recruitment and growth acceleration may be faster when ELJs or natural WM jams are so extensive as to cause reach-scale aggradation and channel anastomosis. Existing information on overall riparian tree sizes in Upper Columbia tributaries is insufficient (e.g., using USBR, 2009) to determine how long it may be before substantial quantities of key members may be recruited to affect reach-scale geomorphic processes.

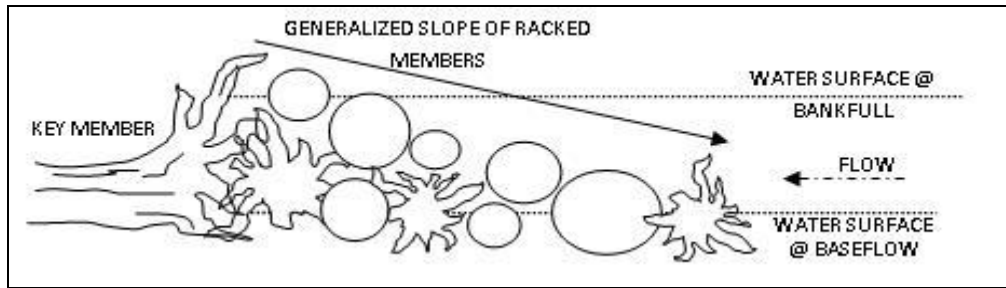
### ***Orientation Patterns***

For both jam types, key and secondary members are always oriented roughly parallel to bankfull flow. This means they were aligned by the river, regardless of the original recruitment direction, with the rootwad facing upstream. Racked members in mid-channel jams are perpendicular to flow, whereas they range from 0 – 280° in deflector jams. Those pieces at the upstream edge which have been most recently recruited are often still aligned parallel to flow, but those older logs closer to the key members are now oriented orthogonal to the thalweg (Figure 3). Designers should note this pattern for constructing deflector jams as it gradually directs the thalweg away from the bank and helps to protect the key and secondary members from the greatest velocities (except when flows overtop the entire structure).

For both mid-channel and deflector jams there also appears to be an inverse longitudinal slope from key members to the upstream extent of racked members (Figure 4). That is, over time the river pushes older racked members higher as they approach the key members, whereas newer (upstream) racked members are generally floating at the water surface. This would seem to functionally reduce shear stress toward the core of the jam and further protect the key members at river stage rises. Quantitative analysis of the range of slopes observed was not possible with the level of topographic data collected. We intend to further investigate this element with subsequent data collection.

### ***Depositional Patterns***

Presumably, the longer depositional bar observed behind mid-channel jams is due to the greater effect they have on interruption of sediment transport than deflector jams. Mid-channel jams create a strong flow separation envelope with bedload moving on both sides of the WM and considerable flow through the structure. Bank-oriented WM typically deflects most bedload and suspended sediment along the wetted face of the jam, while less discharge is through or landward of the structure. Further exploration of these relationships would assist ELJ designers in predicting the spatial effect of varying structure sizes.



**Figure 4. Diagram showing inverse longitudinal slope of racked members.**

### ***Reach-Scale Accumulation Patterns and Loading***

Our study did not examine enough log jams in a continuous reach to describe reach-scale spatial patterns of deposition. However, the air photo time-series analysis (Appendix A) shows that log jams formed on the outside of meanders when single key members became lodged and when they accumulated in shallow, depositional environments such as point bars. Jams also formed *in situ* when lateral channel migration caused large trees to fall into the river and become key members, consequently recruiting secondary and racked members. Both jam types can subsequently redirect the thalweg and initiate formation of additional jams through accelerated recruitment. This demonstrates that it is too simplistic for restoration practitioners to install ELJs only in “likely accumulation areas.” Instead, we suggest that it is more important to construct ELJs in locations which meet site-specific objectives, where a cause-and-effect is desired (e.g., flow deflection, riffle formation, sediment retention), or simply to increase overall habitat complexity. However, restoration of reach-scale geomorphic processes [by constructing numerous WM jams] should be paramount to development of habitat objectives at any single structure.

In physical modeling experiments, Luzi et al. (2011) found that a threshold existed where WM volume above or below this value results in markedly different expressions of channel planform, dimension, and profile. In natural, alluvial systems this implies that considerable WM additions must occur at the reach-scale in order to achieve instream habitat complexity that nears pre-disturbance conditions. Current ELJ projects in the Upper Columbia Region are likely of insufficient quantity and longitudinal scope to exceed this desirable—though unknown—threshold.

### ***Geomimetic Design***

The use of geomimetics to mimic the structure and function of natural log jams in ELJ design should produce high-quality, persistent structures for watershed restoration applications. This method may also inherently capture some of the site-specific characteristics that are otherwise too complex to model using traditional numerical tools.

As a consequence however, this may reduce the engineering factor of safety and thus only be suited to locations where the risk of losing or gaining some logs over time is an acceptable result.

Designers using this method should first use aerial photography to validate the persistence of natural log jams in a particular area. Care should be taken to select the appropriate strata (i.e., stream type, valley type, hydrology, boundary conditions) when surveying “reference log jams” that are directly applicable to the treatment reach. Next, field surveys should carefully measure many of the attributes described in this paper to quantify those elements which beget stability in that particular location and geomorphic setting. Certain log jam features will most likely require estimation (e.g., burial depth of lowest logs, number of pieces below water surface).

The replication of these attributes in the construction of ELJs is perhaps the most difficult part of the process. Those individuals who surveyed the natural analogs should be in charge of materials selection, supervise individual log placement, and be continually present during construction to adequately replicate small but potentially important design features. Many ELJ characteristics are not easily depicted in engineering drawings and are more efficiently communicated in-person with contractors and equipment operators.

Smaller racked members, branches, needles and leaves may also dissipate incoming stream energy and provide excellent surfaces for macroinvertebrate colonization.

### ***Opportunities for Improving ELJ Designs***

The natural jams studied in the White River exhibit several characteristics that are different than most ELJs which have been constructed in the Upper Columbia region. To better mimic these reference jams, we present a number of observations from this work which should increase the similarity of constructed to natural jams.

Key, secondary, and racked members exhibited a very wide range of log sizes and lengths. The racked material consisted of many pieces packed tightly together which appears to functionally reduce velocity and shear forces on the key and secondary pieces. In addition, extensive racked members provide excellent fish habitat by creating cover, high flow refugia, and a substrate for macroinvertebrate colonization. Our observations of recently constructed ELJ projects within the Upper Columbia indicate that most designers utilize only large logs, omitting smaller pieces and slash. This creates a myopic focus on component stability—often at the expense of habitat complexity—within the jam.

The natural WM accumulations we studied were also largely porous, even under baseflow conditions. This creates excellent, complex habitat for fish which is not replicated by an impermeable ELJ ballasted with excavated fill or imported material.

While some key pieces may be backfilled with *in-situ* material (excavated and placed below the predicted scour depth), we observed many local ELJs that offer only the leading edge of placed logs as available aquatic habitat. Self-ballasted structures—with components that partially float at different stages—indeed pose some engineering uncertainty, but also provide considerably more surface area for fishes to seek local high-flow and thermal refugia. The height of stacked logs in the ELJ should be conservatively scaled to exceed bankfull elevations.

ELJ structures are generally designed to be rigid (i.e., non-deformable) and remain in place for a minimum period of time (often 10+ years, in our experience). To meet the objective of providing stable habitat over time, many local ELJs are constructed with large rock for ballast and often fortified with steel cable, even when installed along the streambanks where they may not be subject to the highest shear forces found in the thalweg. Cables sometimes break (creating public safety hazards) and large rock is often geomorphically inappropriate in finer-grained valleys. Observations in the White River demonstrate that natural WM jams can indeed be stable without large rock or artificial ballast.

The annual collection and shedding of ice is a phenomenon which is common among mainstem log jams in this area but is less frequent in the better-studied western Washington rivers. The deformability of natural log jams would seem to be a key element that enables them to temporarily accrue passing ice and withstand the powerful torqueing and floating forces which ensue. ELJs which allow for deformation may survive these ice events better than those with only rigid elements.

We have observed several ELJ projects that leave regular gaps between individual log structures. This may inadequately protect the new streambank from eddy scour due to reciprocal flow caused by the upstream ELJ. Deflector jams which provide continuous WM along the streambank—particularly for bank revetment projects—should minimize vortex erosion in the lee of each structure.

Another common practice among designers is to place all trees with root wads facing into the wetted channel. The bole is typically buried and ballasted within the streambank. We presume this practice is done because roots afford greater surface area available as habitat and perceived shear stress reduction is greater than the bole? However, all of the reaches in the White River that we examined contained trees which fell into the channel with the rootwad still intact on the bank. Since the rootwad can comprise 20% or more of the tree weight, it may act as a ‘deadman anchor’ when buried within the bank and enhance stability. Rootwads placed in the active channel also create more turbulence than a smooth bole and can cause unintended scour along the streambank it is designed to protect. Varying the orientation of WM would better mimic natural log jams.



Logs that are perennially submerged or buried beneath saturated soils are considerably heavier than the dry (or even green) weight of trees obtained for ELJ construction. For example, Shields et al. (2001) found that completely saturated trees weigh 137% more than *in-situ* samples (including both dead and living trees). Therefore, prior to ELJ construction, it would be preferable to stage key and secondary member logs in a wetted environment for several weeks or more so that they are less buoyant when placed in the final structure. This may sometimes be possible in an off-channel pond environment or if tethered within the treatment reach the season prior.

Montgomery and Abbe (2006) demonstrated that log jams abandoned by the active channel later become “hard points” in the floodplain. Aggradation often occurs behind the jam which is later abandoned as the channel migrates laterally across the valley. These newly elevated areas beget old-growth forest development over a period of many centuries and a patchwork of diversity develops on the floodplain. Thus, they speculate that a positive feedback mechanism exists by which log jams support riparian forest development. This, in turn, provides more large wood for the development of more log jams and further influences alluvial channel dynamics. Concurrent with this idea, we suggest that restoration practitioners build more ELJs buried in the floodplain or in abandoned meander scrolls where they would someday be expected to interact with the active channel. Floodplain ELJs may also be easier to implement given the difficulties of obtaining in-stream permits and the social constraints often faced when adding WM to rivers. This would promote a positive trajectory for long-term ecological health and stream channel-floodplain connectivity, and serve as an example of ‘holistic’ or ‘process-based’ restoration in practice.

### ***Regional Differences***

General patterns and processes of WM accumulations in the White River are similar to observations from other watersheds (e.g., frequent jams can store considerable sediment, cause local aggradation, redirect flows, etc.), although the size and distribution of wood appears regionally distinct.

WM accumulations are clearly an important habitat feature in both wet and dry environments. The eastern Cascades region exhibits a steep precipitation gradient from west to east and vegetative conditions reflect that. Vegetation growth is more vigorous in the wetter, steeper mountain reaches farther west, although discharge increases eastward toward the Columbia River. Such dramatic gradients are not as prominent in the western Cascades where riparian areas are extremely vigorous across the landscape. A common question then arises among restoration planners as to how much WM should be placed in a particular reach. We suggest that reference wood loading volumes would be difficult to determine because: 1) reference reaches do not exist in many of the lower-elevation, mainstem east Cascades rivers where restoration planning is currently underway; 2)

reference reaches generally only exist in the mountains which display an inverse relationship between riparian vegetation potential and discharge eastward toward the Columbia River; and 3) socio-political constraints in the mainstem Wenatchee, Entiat, Methow, and Okanogan Rivers make attainment of reference WM volumes unlikely. Instead, we advocate further study to determine the structural characteristics of stable, persistent WM jams in the east Cascades region which can be broadly applied to streams of different sizes and vegetative communities at variable loading rates.

Fox and Bolton (2007) provide regional WM load planning targets for land managers based on their study of WM reference conditions. They, like other authors, note a positive correlation between increasing WM volume and stream size until discharge becomes so great that is capable of moving even the biggest trees available (Swanson and Lienkaemper, 1978; Bilby and Ward 1989). Abbe and Montgomery (2003) suggest that this drainage area maxima is around 300 km<sup>2</sup> for streams on the Olympic Peninsula (WA). The drainage area at our study locations ranged from 238 km<sup>2</sup> to 355 km<sup>2</sup>. Fox and Bolton (2007) also noted a similar pattern of WM volume across numerous Washington rivers, but instead used bankfull width as a metric to describe increasing stream size. They also noted >6x the WM volume for western Washington streams than for eastern Washington when comparing streams of like size (using the 75<sup>th</sup> percentile). Fox (2001) provides some figures for minimum key piece volumes for eastern Cascade streams—10.75m<sup>3</sup> for rivers >50m wide—though he suggests that optimum values would be more than double this amount. More work is needed to determine these volumes if specific quantitative targets in eastern Cascade watersheds must be met.

### ***Additional Questions/Future Research***

Our study could only measure those WM pieces which are visible from the surface. However, all but one jam had numerous logs which were beneath the water and/or bed surface at baseflow. This appears due to local aggradation and self-burial over time, coupled with increasing crescentic and lateral pool scour at the head or side of the structure. Due to the high number of logs beneath the ground and water surface, it is difficult to accurately measure total WM volume for use in force balance calculations. Nonetheless, we suggest that it would be useful to quantify total WM jam volume to determine the range of weight and size characteristics which beget natural stability, particularly since these basal pieces were the original key members which initiated jam formation. However, such methods would be difficult, expensive, and environmentally damaging to perform if a subsample of log jams were excavated for measurement. Other less-invasive technologies such as side-scan sonar may provide useful information on buried or sub-surface WM as well.

Current ELJ design methods usually involve 1- or 2-dimensional hydrologic modeling based on topography, hydrology, and partitioned roughness value estimates of the

structure, bed and streambanks. Many of these models do not additionally account for sediment transport mechanics, though this is clearly an important design consideration. Scaled physical models have the advantage of quantifying sediment flux along with variable quantities and configurations of WM. They can run several decades of variable flow events in a short period of time that are cumulative in nature (i.e., not simply discrete floods which do not account for previous years' flood effects). Physical models also offer an opportunity to test for wood addition thresholds in treatment reaches. These tools should also be used to test site-specific scour dynamics, general numerical model performance and calibration, and the confirming the accuracy of project-specific 1d or 2d modeling predictions for each ELJ constructed.

ELJ designs also rely on quantifying all attendant forces that act on a log jam (e.g., buoyancy, drag, surcharge, etc.) which, invariably, must be estimated for modeling purposes. The real-world complexity and variability of irregular materials like wood are such that it leads designers to specify materials with better-known characteristics (i.e., rock and cable) for ballast. Validation modeling of as-built ELJ performance could enable more precise estimates of forces for modeling and allow for construction of structures that function more like natural, stable log jams without the need for artificial ballast.

Insufficient data currently exists to define minimum length and DBH criteria for stable key and secondary members in this area. A broader survey of WM accumulations would help to determine stability thresholds, relative to stream power, in this hydro-physiographic region (e.g., development of a dimensionless plot similar to Figure 12, Abbe and Montgomery, 2003). A more robust statistical comparison of log sizes (length, DBH) between deflector-type and mid-channel jams may also be useful with a larger regional dataset.

## **Acknowledgments**

We would like to thank the Mid-Columbia River Fishery Resource Office for providing funding and support. We would also like to thank Kate Terrell, William Gale, Mark Nelson, and Jim Craig for their review and critical feedback. We appreciate the numerous conversations and field trips we have had with other local scientists and practitioners who have helped us to develop and refine many of these ideas.

## Literature Cited

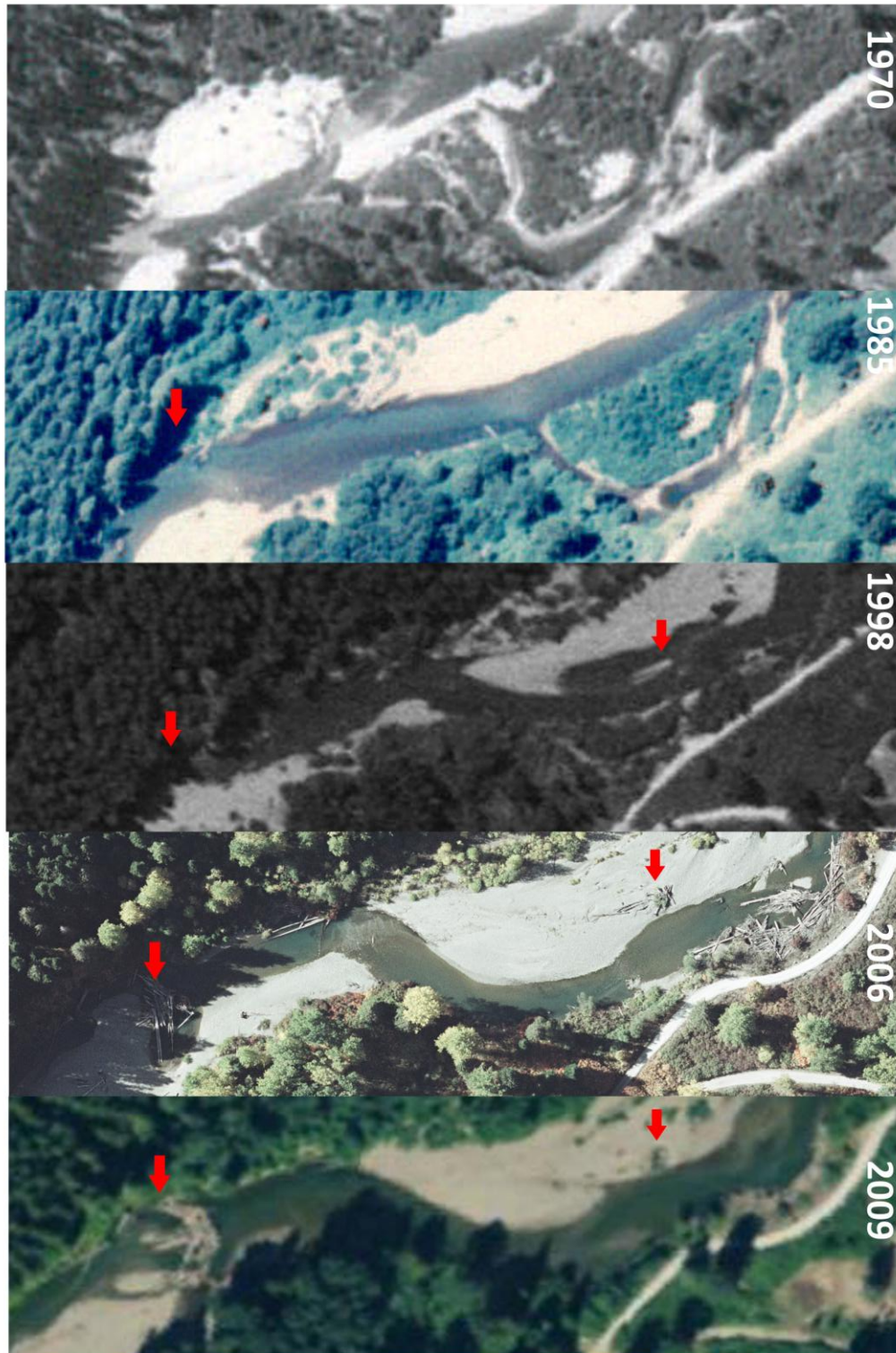
- Abbe, T.B., and D.R. Montgomery. 2003. Patterns and process of wood debris accumulation in forest channels. *Geomorphology* 51:81– 107.
- Bilby, R. E., and J. W. Ward. 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. *Transactions of the American Fisheries Society* 118:368-378.
- Braudrick, C.A. and G.E. Grant. 2000. When do logs move in rivers? *Water Resources Research*, 36(2):571-583.
- Brummer, C.J., Abbe, T.B., Sampson, J.R., and D.R. Montgomery. 2006. Influence of vertical channel change associated with wood accumulations on delineating channel migration zones, Washington, USA. *Geomorphology* 80:295-309.
- Fox, M. J. 2001. A New Look at the Quantities and Volumes of Instream Wood in Forested Basins within Washington State. M.S. Thesis, Univ. of Washington. 202pp. Available online at: <http://water.washington.edu/Theses/Fox-2001-Thesis.zip>
- Fox, M.J. 2003. Spatial organization, position, and source characteristics of large, woody debris in natural systems. PhD dissertation, Univ. of Washington. 133pp. Available online at: <http://water.washington.edu/Theses/fox.2003.pdf>
- Fox, M.J., and S.M. Bolton. 2007. A regional and geomorphic reference for quantities and volumes of instream wood in unmanaged forested basins in Washington State. *N. Am. J. Fish. Mgmt.* V.27:1. pp. 342-359.
- Harmon, M. E., J. F. Franklin, F. J. Swanson, P. Sollins, S. V. Gregory, J. D. Lattin, N. H. Anderson, S. P. Cline, N. G. Aumen, J. R. Sedell, G. W. Lienkamper, et al. 1986. *Ecology of Coarse Woody Debris in Temperate Ecosystems. Advances in Ecological Research.* A. MacFadyen and E. D. Ford. New York, NY, Harcourt Brace Jovanovich. 15: 133-302.
- Hicks, B. J., Hall, J.D., Bisson, P.A., and J. R. Sedell. 1991. Responses of salmonids to habitat changes. *American Fisheries Society Special Publication* 19:483-518.
- Lassettre, N.S. and R.R. Harris. 2001. The geomorphic and ecological influence of large woody debris in streams and rivers. Univ. of California, Berkeley.
- Luzi, D.S., Davidson, S., and B. Eaton. 2011. Dynamics of Mountain Rivers: Insights from physical models. *Innovation* 15:2. pp. 33-36. Available online at: <http://innovation.digitalityworks.com/issues/2011/MarApr/MarchApril2011web.pdf>

- Montgomery, D.R. and T.B. Abbe. 2006. Influence of logjam-formed hard points on the formation of valley-bottom landforms in an old-growth forest valley, Queets River, Washington, USA. *Quaternary Research* 65(1):147-155.
- Naiman, R.J., Fetherston, K.L., McKay, S., and J. Chen. 1998. Riparian forests. In: Naiman, R., Bilby, R.E. (Eds.), *River Ecology and Management*. Springer-Verlag, New York, pp. 289– 323.
- Robison, E.G.; Beschta, R.L. 1990. Characteristics of coarse woody debris for several coastal streams of southeast Alaska, USA. *Canadian Journal of Fisheries and Aquatic Sciences*. 47: 1684-1693.
- Rosgen, D.L. 1994. A classification of natural rivers. *Catena* 22:169-199.
- Schuett-Hames, D., Pleus, A.E., Ward, J., Fox, M., and J. Light. 1999. TFW Monitoring Program Methods Manual for the large woody debris survey. Prepared for the Washington State Dept. of Natural Resources under the Timber, Fish, and Wildlife Agreement. TFW-AM9-99-004. DNR #106. March.
- Shields, F. D., Jr., Morin, N. and C.M. Cooper. 2001. Design of large woody debris structures for channel rehabilitation. In: U. S. Subcommittee on Sedimentation. Proceedings of the Federal Interagency Sedimentation Conferences, 1947 to 2001, Seventh Conference Proceedings, CD-ROM, Washington, D. C. Available online at: [http://www.ars.usda.gov/sp2UserFiles/person/5120/large\\_woody\\_debris.pdf](http://www.ars.usda.gov/sp2UserFiles/person/5120/large_woody_debris.pdf)
- Swanson, F. J. and G. W. Lienkaemper. 1978. Physical consequences of large organic debris in pacific northwest streams. USDA Forest Service, General Technical Report, PNW-69.
- Tally, T. 1980. The Effects of Geology and Large Organic Debris an Stream Channel Morphology and Process for Streams Flowing Through Old Growth Redwood Forests in Northwestern California. Doctor of Philosophy. University of California, Santa Barbara, Santa Barbara, CA, 273 pp.
- UCSRB. 2007. Upper Columbia Spring Chinook Salmon and Steelhead Recovery Plan. Wenatchee, WA. 352pp. Available online at: <http://www.ucsrb.com/UCSRP%20Final%2009-13-2007.pdf>
- USBR. 2009. Entiat Tributary Assessment, Chelan County, Washington. U.S. Dept. of Interior, Bureau of Reclamation, Technical Services Center, Denver, CO. 92pp. Available online at: <http://www.usbr.gov/pn/programs/fcrps/thp/ucao/entiat/tribassmt/index.html>
- Woodsmith, R.D. and A. Bookter. 2007. Initial geomorphic assessment for river restoration: An example from the Entiat River, Washington. USDA Forest

Service, Pacific Northwest Research Station, Wenatchee Forestry Sciences Laboratory, Wenatchee, WA. 23pp.

## APPENDIX A

### Aerial Photo Time-Series of Surveyed Log Jams



**Figure 5. Bar-apex #1 (lower) and #2 (upper). Red arrows indicate conclusive presence and location of log jam.**





**Figure 6. Deflector-type jam #1 (upper) and #2 (lower). Red arrows indicate conclusive presence and location of log jam.**



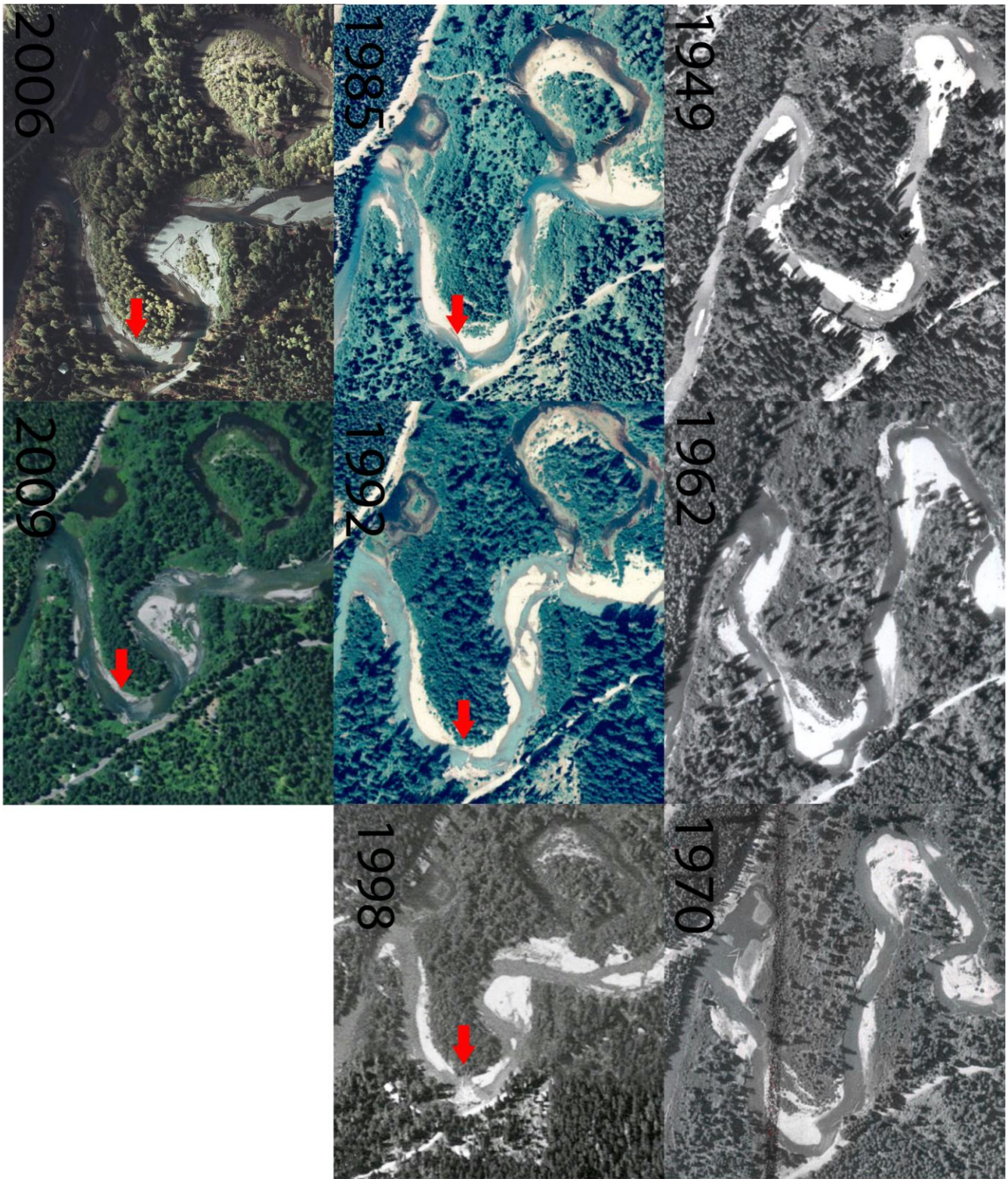


Figure 7. Deflector-type jam #3. Red arrows indicate conclusive presence and location of log jam.

**U. S. Fish and Wildlife Service  
Mid-Columbia River Fishery Resource Office  
7501 Icicle Road  
Leavenworth, WA**



**February 2012**